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THEORIES OF THE ORIGIN OF MOUNTAIN RANGES.

MOUNTAINS are the focal points of geological interest. In their complex structure are contained all kinds of rocks, sedimentary, eruptive and metamorphic; and in their formation are engaged all geological forces in their greatest intensity. They are the culminating points, the theatres of greatest activity of all geological agencies; igneous agencies in their formation, aqueous agencies by sedimentation in their preparation, and by erosion in their subsequent sculpture. Their discussion, therefore, is a summation of all the principles of structural and dynamical geology. But they are equally important in historical geology, for the birth of mountains marks the times of great revolutions in the history of the earth, and therefore determine the primary divisions of geological time. Evidently therefore the theory of mountains lies at the very basis of theoretic geology, and a true theory must throw abundant light on many of the most difficult problems of our science.

But if this is the most important, it is also the most difficult of all geological questions. My object now is to give, as briefly as possible, the present condition of science on this subject. But in all complex subjects there is a region of comparative certainty and a region of uncertainty; a region of light and a region of twilight. My farther object, therefore, will be to separate sharply these two regions from one another, and thus to clear the ground, narrow the field of discussion and direct the course of profitable investigation.

But first of all I must define my subject. A mountain range is a single *mountain individual*—born at one time (monogenetic) *i.e.*, the result of one—though it may be a prolonged—earth-effort; as contra-distinguished on the one hand from a mountain *system* which is a family of mountain ranges born at different times (polygenetic) in the same general region; and on the other from ridges and peaks which are subordinate parts—limbs and organs—of such a mountain individual. Now a theory of mountains is essentially a theory of mountain ranges, as thus defined. In all that follows, therefore, on the subject of mountain structure and origin, we refer to mountain ranges.

STRUCTURE OF MOUNTAINS.

The origin of mountains is revealed in their structure. We must, therefore, give briefly those fundamental points of structure on which every true theory of origin must be founded.

1. *Thickness of Mountain Sediments.*—The enormous thickness of mountain strata is well known, but it is impossible to overstate its fundamental importance. We therefore give some striking examples. The Palæozoic rocks involved in the folded structure of the Appalachian, according to Hall, are about 40,000 feet thick. The Palæozoics and the Mesozoics in the Wasatch, according to King, are about 50,000 feet thick. The Cretaceous alone, in the Coast Range of California near the Bay of San Francisco, according to Whitney, are 20,000, and in Shasta county, according to Diller, are 30,000 feet thick. The Mesozoics and Tertiaries of the Alps, according to Alpine geologists, are 50,000 feet.[1] The upper Palæozoic and Mesozoic of the Uinta, according to Powell, are 30,000 feet. These are conspicuous examples, but the same is true of all mountains.

It might be objected that these numbers express the general thickness of the stratified crust everywhere—only that in mountains the strata are turned up and their thickness exposed by erosion. But this is not true. For in many cases the strata may be traced away from the mountain; and in such cases they always *thin out* as distance increases. For example, the 40,000 feet of

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[1] JUDD: Volcanoes, p. 295.

Appalachian Palæozoics thin out going west until at the Mississippi river they are only 2000 to 4000 feet. The Palæozoics which in the Wasatch are 30,000 feet thin out eastward until they are only 1000 feet on the plains. It follows then that *mountains are lines of exceptionally thick sediments.*

2. *Coarseness of Mountain Sediments.*—Mountains are composed mainly of grits, sandstones, and shales, *i.e.*, of mechanical sediments, and most conspicuously so along their axial regions. As we go from this region, sometimes in either direction, but especially in one direction, the strata become finer and finer; sandstones giving way to shales and shales to limestones, *i.e.*, mechanical to organic sediments. This is conspicuously true of the Appalachian; in so many ways a typical mountain. As we pass from the eastern ridge westward, grits and sandstones are replaced by shales and these by limestones. Therefore mountains are also *lines of exceptionally coarse sediments.*

3. *Folded Structure of Mountains.*—The folded structure of mountains is perhaps the most universal, and certainly the most significant, of all their features. But there is great variety in the degree and complexity of the foldings. Sometimes the mountain rises as *one* great fold. The Uinta is an example of this. Sometimes and oftener there are *several open* folds, like waves of the sea. The Jura is a good example of this. Sometimes and oftenest of all, there are *many closely appressed* folds. This is the case in the Coast Range of California, in the Appalachian, in the Alps, and probably in the Sierra. The Appalachian may be taken again as the type. In this range the folds are most numerous and most closely appressed in the axial region, and open out and die away in gentle waves as we go westward. Finally, sometimes in extreme cases, as in the Alps, the Pyrenees and probably the Sierra, the strata of the lateral slopes are thrust in under the central and higher parts, so that the strata of these central parts are overfolded outwards on one or both sides. This is the *Fan-structure*, so marked in the Alps and Pyrenees, where the underthrust and overfold are on both sides, but found also in the Appalachian and Sierra, where they are on one side only.

Amount of Folding.—Folded structure implies, of course, an alternation of anticlines and synclines. The number of these varies with the intensity of the folding. In the Coast Range there are apparently four or five anticlines and corresponding synclines. In the Sierra they cannot be counted, but there must be very many so closely appressed that the strata seem to be a continuous series dipping all in the same direction, *i.e.*, steeply toward the axis, for at least 30 miles. They cannot form a single series, for this would make an incredible thickness. It must be a series repeated several times by extreme folding; how many, it is impossible now to say. In the Appalachian, according to Claypole[1], there are about 19 anticlines and synclines in 65 miles and in one part—Cumberland valley—there are eight in 16 miles. In the Vaudoise Alps, according to Renevier, there are at least seven[2], and in Savoy as many as 15[3]. In many cases the foldings are so extreme that the strata first rise as folds, then are pushed over beyond the base as overfolds, and finally broken at the crest and upper limb of the fold is pushed over the lower limb many miles horizontally. In the Highlands of Scotland, according to Peach[4], by overthrust, the Archæan is brought over the Silurian and overrides it for ten miles. In the Rocky Mountains of Canada, according to McConnell[5], the Cambrian is brought over the Cretaceous and overrides it for seven miles. In the Appalachian of Georgia, according to Hayes[6], by overthrust, the Cambrian is made to override the Carboniferous for eleven miles.

4. *Cleavage Structure.*—Closely connected with the last, and having a similar significance, viz., lateral squeezing and mashing, is another structure—*cleavage.* This structure is often asso-

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[1] Am'n Nat'st, Vol. 19, p. 257 and seq.

[2] Archives des Science, Vol. 59, p. 5, 1877.

[3] Archives, Vol. 28, p. 608, 1892, and 25, p. 271, 1893.

[4] Nature, Vol. 31, p. 29, 1884.

[5] Geol. Surv. Can. 1886, Rep. D. p. 33.

[6] Bull. Geol. Soc. Am. Vol. 2, p. 141.

ciated with folding and both with mountain ranges. It is not so universal as folding only because all kinds of strata are not equally affected by it; being well exhibited only in fine shales. It is important to observe that in slaty cleavage the *strike* of the cleavage planes is the same as that of the strata, and both the same as the trend of the mountain; and that the *dip* of the cleavage planes is nearly or quite vertical. Whole mountains are thus cleavable from top to bottom.

5. *Granite or Metamorphic Axis.*—Some mountains are made up wholly of folded strata. This is the case with the Appalachian, the Coast Range, and the Jura. But most great mountains consist of a granitic or metamorphic axis with stratified flanks. This is conspicuously the case with the Sierra, the Alps, and most other great mountains. So general is this, that the typical structure of ranges may be said to be—a granitic axis forming the crest, and stratified rocks, more or less folded, outcropping on the slopes. This very characteristic structure ought to be explained by a true theory of origin.

6. *Asymmetric Form.*—Mountains are not usually symmetric, with crest in the middle and slopes equal on the two sides. On the contrary they usually have a long slope on one side and a steeper, often a very abrupt, slope on the other. The crest or axis is not in the middle but nearer to one side. The earth-wave seems ready to break and often does break with a great fault on the steeper side. The Uinta is perhaps the simplest example. This range rises as a single great fold, but steeper on the north side where there is a fracture and fault of 20,000 feet vertical. Of course in this as in all cases the original fault-cliff has crumbled down to a steep slope, or even been destroyed entirely. The Sierra and Wasatch are remarkable examples of asymmetry. The Sierra rises on the west side from the San Joaquin plains near sea level by a gentle slope fifty to sixty miles long, reaches its crest near 15,000 feet high and then plunges down by a slope so steep, that the desert plains on the east, 4,000 to 5,000 feet above sea level is reached in six to ten miles. There is on this side a fault-cliff nearly 11,000 feet high. The Wasatch

has a similar form, except that the fault-cliff looks westward instead of eastward. It is true that the extreme asymmetry of these two mountains was given them long after their origin and by a different process to be presently described. But even before this last movement they were probably asymmetric, though in a less degree. The Appalachian is perhaps here again a typical mountain. Its long slope is to the west and its crest close to the eastern limit. The Alps, the Appenines, the Carpathians, and the Caucasus, according to Suess, are foreign examples of the same form.

There are many other interesting points of structure that might be mentioned, but they are less significant of mode of origin and therefore omitted in this rapid sketch.

ANOTHER TYPE OF MOUNTAINS.

I have given the main characteristics of mountains of the usual type, of which the Appalachian, the Coast Range, the Alps and Pyrenees may be taken as good examples. But there is another type, different in structure and in mode of origin, to which attention, I believe, was first called by Gilbert. It is doubtful if they are found anywhere except in the Basin and Plateau regions, and therefore the type may be called the Basin region type. The Basin and Plateau regions are broken by north and south fissures into great crust-blocks which by gravitative readjustment have been tilted, *i. e.*, one side heaved up and the other side dropped down, so as to form a series of north and south ridges and valleys. Each ridge rises by a long slope on one side to a crest and then drops by a steep fault-cliff on the other. The ridges therefore are extremely asymmetric but the asymmetry is produced in a different way from that of the usual type. In a word, these mountains seem to be the result of a series of enormous parallel faults. Such faults are common everywhere, but do not usually give rise to any inequalities which may be dignified by the term mountain: or if so at one time, have since been levelled by erosion. But those in the Basin region are on so grand a scale and so recent in time, that they form very conspicuous orographic features. I have sometimes doubted whether they should be called ranges at all; but when we reflect that at least 10,000 feet of the height of the Sierra is due to normal faulting, it seems impossible to withhold the term. Thus mountains may be divided into two types, viz., mountains formed by folding of strata and mountains formed by tilting of crust-blocks. The structure of the one is *anti*clinal or *di*clinal, of the other *mono*clinal. The Sierra probably belongs to both types. It was formed at the end of the Jurassic as a mountain of the first type, but the whole Sierra block was tilted up on its eastern side without folding, at the end of the Tertiary, and it then became also a mountain of the second type.

A complete theory must explain this type also; but since from its exceptional character it must be regarded as of subordinate importance, we shall be compelled to confine our discussion to mountains of the usual type.

EXPLANATION OF THE PRECEDING PHENOMENA.

In all cases of complex phenomena there have been many theories, becoming successively more and more comprehensive. The citadel of truth is not usually taken at once by storm, but only by very gradual approaches. First comes the collection of carefully observed facts. But bare facts are not science. They are only the raw material of science. Next comes the grouping of these facts by laws more or less general. This is the beginning of true science. Every such grouping or reducing to law is a scientific explanation, and therefore in some sense a theory. At first the grouping includes only a few facts. The explanation or theory lies so close to the facts as to be scarcely distinguishable from them. It is a mere corollary or necessary inference. It is modest, narrow, but also in the same proportion *certain*. Then the group of explained facts becomes wider and wider, the laws more and more general, and the theory more daring (but in the same proportion also perhaps more doubtful): until it may at last include the Cosmos itself in its boundless but shadowy embrace.

Now in this gradual approach toward perfect knowledge, there are two very distinct stages. The one consists of explanation of the immediate phenomena in hand. This gives the laws of the phenomena, and may be called the *Formal Theory*. The other explains the cause of these laws, and may be called the *Causal or Physical Theory*. All science passes through these two stages. For example: Until Kepler, the phenomena of Planetary motion were a mere chaotic mass of observed facts without uniting law. Kepler reduced this chaos to order by the discovery of the three great laws which go by his name. This is the *formal* theory of Planetary motion. But still there remained the question, why do planets move according to these beautiful laws? Newton explained this by the law of gravitation. This is the causal or *physical* theory.

But this is so important a distinction that I must illustrate by examples taken from geological science. All the phenomena of slaty cleavage are completely explained by supposing the whole rocky mass to have been mashed together horizontally and extended vertically. This is the Formal theory and may be regarded as certain. But still the question remains: How does mashing produce easy splitting in certain directions? The solution of this question is the Physical theory, and is perhaps a little more doubtful, though I think satisfactorily answered by Tyndall. But still there remains a deeper and more doubtful question, Whence is derived the mashing force? Is it general interior contraction, as some think, or is it local expansion as others think. A perfect theory must answer all these questions. Take another example: All the phenomena of the drift are well explained by the former existence of an ice sheet moving southward by laws of glacial motion, scoring, polishing, and depositing in its course. This is the Formal theory. But still the question remains, What was the cause of the ice sheet? Was it due to northern elevation, or to Aphelian winter concurring with great eccentricity of the earth's orbit? And if due to northern elevation, what was the cause of that elevation? A perfect theory must answer all these questions. Take one more example: All the phenomena of earthquakes are completely explained by the emergence on the surface and a spreading there from a centre, of a series of elastic earth-waves. This is the Formal theory. It explains the immediate facts observed here on the surface, but no more. But still remains the question, What is the *cause*, deep down below, of the concussion which determined the series of earth-waves. This, the physical theory, is far more doubtful. Or the theory may be made still deeper and proportionately more doubtful. If our theory of the cause of the interior concussion be the formation of a fissure or readjustment of a fault, as seems in many cases probable, there would still remain the question of the cause of great fissures and of their subsequent readjustment by slipping. This is probably as far as geological theory would go: for although cosmogony may go still farther, the interior heat of the earth is usually the final term of strictly geological theories.

I have made this long detour because I wish to keep clear in the mind these two stages of theorizing in the case of Mountain Origin. The formal theory is already well advanced toward a satisfactory condition; the physical theory is still in a very chaotic state. But these two kinds of theories have been often confounded with one another in the popular and even in the scientific mind and the chaotic state of the latter has been carried over and credited to the former also; so that many seem to think that the whole subject of mountain-origin is yet wholly in air and without any solid the foundation.

I. FORMAL THEORY.

A true formal theory, keeping close to the immediate facts in hand, must pass gradually from necessary inferences from smaller groups, to a wider theory which shall explain them all.

Inferences from 1 and 2, i. e., Thickness and Coarseness of Sediments.—The thickness of mountain sediments, as we have seen, is greatest along the axis and grows less as we pass away from that line. Now where do we find lines of very thick sediments forming at the present time? The answer is: On sea bottoms closely bordering continents. The whole washings of continents accumulate very abundantly along shore lines and thin out seaward. Mountains were therefore born of sea-margin deposits. This view is entirely confirmed by the character of mountain sediments. We have seen that these are coarsest near the crest, becoming finer and then changing into limestones as we pass farther and farther away from the crest. Now this is exactly what we find in off-shore deposits. They are coarse sands and shingle near shore, and then become progressively finer seaward, until in open sea beyond the reach of even the finest mechanical sediments, they are replaced by organic sediments which form limestones. It seems evident, therefore, that the place of a mountain-range before mountain-birth was a marginal sea-bottom receiving abundant sediment from a contiguous continental land-mass. This explains at once the usual position of mountains on the borders of continents. Here, then, is one important point gained.

But such enormous thickness as we often find would be impossible unless the conditions of sedimentation on the same spot were continually renewed by *pari passu* subsidence of the sea-bottom. And we do indeed find abundant evidence of such *pari passu* subsidence, not only at the present time in places where abundant sediments are depositing, but also in the strata of all mountain ranges. In the 40,000 feet thickness of Appalachian strata nearly every stratum gives evidence by its fossils, of shallow water, and often by shore marks of all kinds, of *very* shallow water. Therefore the place of mountains while in preparation, in embryo, before birth, *was gradually subsiding, as if borne down by the weight of the accumulating sediments*, and continued thus to subside until the moment of birth, when of course a contrary movement commenced. The earth's crust on which the sediments accumulated was bent into a great trough, or what Dana calls a Geo-Syncline. This is another important poined gained.

But let us follow out our logic. If the earth's crust yields under increasing weight of accumulating sediments, then ought it also to rise under the decreasing weight of eroded land surfaces. If it sinks by loading it ought also to rise by unloading.

And such indeed seems to have been the fact. For if all the strata which have been removed from existing plateaus and mountains were restored, it would make an incredible height of land. At least 10,000 to 12,000 feet have been carried away by erosion from the Colorado Plateau region and yet 8,000 feet remain. At least 30,000 feet have been worn away from the Uinta Mountains and yet 10,000 feet remain. Evidently there has been a rise *pari passù* with the lightening by erosion.

May we not then safely generalize? May we not conclude with Dutton that the earth in its general form and in its greater inequalities is in a state of gravitative equilibrium—that the earth is oblate spheroid, only because this is the form of gravitative equilibrium of a rotating body; that ocean basins and continental protuberances exist, only because the materials underlying the former are denser, and underlying the latter lighter than the average. It is true that the spheroid form of the earth and the sinking and rising of the crust by loading and unloading may be explained on the supposition that the earth is liquid beneath a thin crust, but to this view there are three fatal objections. 1. The cosmic behavior of the earth is that of a rigid solid. This I believe to have been demonstrated. 2. The existence of the present great inequalities of the earth would be impossible, except under the most improbable conditions. For example, if the earth be fluid then the crust must rest as a floating body. But if so, then, by the laws of floatation, for every continental protuberance on the upper side there must be a corresponding protuberance in reverse on the other side of the crust, and for every great plateau or mountain range there must be a corresponding plateau or mountain range in reverse. And taking the difference of specific gravity of the floating crust and the supporting liquid to be as great as that between ice and water, these reverse inequalities must be ten times as great as those at surface! Can we accept so violent an hypothesis? But (3) repeated experiments, especially very recent ones by Carl Barus,[1] prove that rocks increase very notably in density in the act of solidification, so that a solid crust would undoubtedly break up and sink in a liquid of the same material. But how then are we to explain gravitative equilibrium in the case of a rigidly solid globe. I answer, by two suppositions. 1. That the earth, though rigid as glass or even steel, to *rapidly* acting force, yet yields *viscously* to heavy pressuse *over large areas* and acting *for a long time.* A solid globe of glass six feet in diameter will very perceptibly change form under its own weight. How much more the earth under its own gravity. This completely explains the oblateness of the earth even if solid throughout and had never been liquid at all. The earth, though rigid, behaves like a very stiffly viscous body ; like, for example, the ice of glaciers though very much more stiffly viscous. This viscosity would not at all interfere with its rigidity under the tide-generating influences of the sun and moon — for these are far too rapidly acting.

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[1] Am. Journal, vol. 45, p. 1., 1893.

2. The second supposition necessary is, that the earth is *not* absolutely *homogeneous* either in density, or in conductivity for heat, that in secular cooling and contraction the denser and more conductive areas, cooling and contracting faster, went down and became the ocean basins, while the lighter and less conductive areas were left as the more prominent land surfaces. And thus to-day the ocean basins are in gravitative equilibrium with the continental areas, because in proportion as oceanic radii are shorter are the materials also *denser;* and in proportion as the continental radii are *longer*, are the materials also specifically *lighter.* This condition of gravitative equilibrium Dutton calls *Isostasy.*

Thus then the great inequalities of the earth, constituting ocean basins and continental surfaces, are the result of *unequal radial descent of the earth's surface* by contraction in its secular cooling. This is by far the most satisfactory theory of these *greatest* inequalities.

In thus following the phenomena of Isostasy to their logical conclusion, we seem to have gone beyond the limits of our subject, which is the *theory of mountains:* but the close connection which probably exists between the cause of continents and the cause of mountains justifies the digression, if such it may be called.

Inferences from 3 and 4, Folding and Cleavage.—Still adhering closely to observed facts, there are some necessary inferences from folded structure and cleavage. These structures are indisputable proofs that mountain strata have been subjected to enormous *lateral* pressure at right angles to the trend of the axis, by which the whole mass has been mashed together horizontally. But such horizontal mashing must of necessity produce corresponding up-swelling along the line of yielding. In a word, it is evident that mountains have been uplifted largely, at least, if not wholly, by horizontal mashing. The only question that remains is, Is lateral mashing alone sufficient to produce the highest mountains ? Let us see.

The amount of uplift in such cases would depend on two things, viz., the thickness of the strata and the amount of mashing. Now, as already shown, mountain sediments are 30,000, 40,000 and even 50,000 feet thick. The amount of mashing in many mountains is almost incredible. In the Appalachian it is so extreme that in one place, according to Claypole, ninety-six miles of the original sediments have been crowded into sixteen miles, and the shortening of the whole Appalachian breadth is estimated as eighty-eight miles.[1] In the Alps the shortening is estimated by Heim at seventy-two miles or one-half the original breadth of the sediments.[2] In a word, we may without exaggeration say that, in great mountains, the original space is to the folded space as two to one, or even three to one. Now a crushing of 30,000 feet of sediments into one-half their original space would double their thickness, which is equivalent to a clear elevation of 30,000 feet. But strata are 40,000 and even 50,000 feet thick. Evidently then this method alone is sufficient to account for the highest mountains in the world, even allowing for the enormous erosion which they have suffered.

The same is equally shown by the phenomena of slaty cleavage so often associated with folded structure. Slaty cleavage, as has been demonstrated by experiment, as well as by field observation, is produced by a mashing together of the whole rocky mass in a direction at right angles to the cleavage plane and a corresponding extension in the direction of the *dip* of these planes. Now since the cleavage dip is usually nearly or quite vertical, this means a mashing together *horizontally* and a proportionate extension *vertically*. The amount of mashing together horizontally and extension vertically has been in many cases somewhat accurately estimated. In this case also, as in folding, we have evidence of a mashing of two or even three into one and a corresponding extension vertically of one into two or even three. This amount of extension affecting thick strata is sufficient to account for the highest mountains in the world without resorting to any hypothetical force pushing upward from beneath.

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[1] Amn. Natst. Vol. 19, p. 257.

[2] HEIM: Archives des Sciences, Vol. 64, p. 120, 1878.

There seems therefore to be no reasonable doubt that *mountains are formed wholly by lateral crushing with proportionate upswelling*. This is a very important point gained. Let us hold it fast. This brings me naturally to the next point.

Inferences from 5 and 6, Granitic Axis and Asymmetric Form.— A granitic or metamorphic axis is a very general, though not a universal, characteristic of mountains. The old idea (still held by some) was that fused matter was pushed up through and appeared above, the parted strata along the crest as the granite axis, lifting the strata, as it were, on its shoulders to form the slopes. But it must be observed that the axis is often only metamorphic, not granitic, and moreover that some mountains are composed wholly of folded strata alone. If, therefore, we regard granite as often only the last term of metamorphism, we may more properly speak of the axis of mountains as metamorphic. If so, then it is not necessary to suppose any vertical uprising of fused matter by volcanic forces at all. On the contrary, we would explain the axis thus :

It is evident that accumulating sediments must cause corresponding rise of the interior heat of earth toward the surface so as to invade the lower parts of the sediments and their included water. Now it is well known from the experiments of Daubreé and others, that in the presence of water, even in small quantities, rocks become softened and even hydrothermally fused at the very moderate temperature of 400° to 800° F. It is certain then that such thickness of sediments as we know accumulated in preparation for mountain birth, must have been softened to a degree proportionate to the thickness, and therefore perhaps semi-fused or even fused in their lower parts along the line of *thickest* deposit, and therefore of greatest subsequent elevation. On cooling after elevation, this sub-mountain fused or semifused matter would form a granitic or metamorphic *core* beneath the highest part. The appearance of this core as an axis along the crest is the result not of up-thrust but of *subsequent erosion* greatest along this line.

And this, in its turn, furnishes a key to the location of mountains along lines of thick sediments. For not only the lower parts of such sediments but also the sea-floor on which they are laid down would be hydrothermally softened or even fused. Thus would be determined a line of *weakness*, and therefore a line of yielding to lateral thrust, and therefore also a line of crushing, folding, and upheaval. The folding and the upswelling and the metamorphism would be greatest along the line of thickest sediments and become less as we pass away from that line. In extreme cases, however, the firmer lateral portions might be jammed in under the softer central portions, on one or both sides, and give rise to the Fan-structure character of complexly folded mountains. Or again, in such cases the folds might be pushed clean over and broken at the bend, and then the upper limb slidden over the lower limb even for miles, forming the wonderful thrust-planes of the Alps, the Appalachian and the Rocky Mountains, already described. Thus the phenomena under (5) is completely explained.

But mountains are usually asymmetric, the crest being on one side. This is explained as follows: Sedimentary accumulations along shore lines are thickest *near* shore (though not *at* shore) and thin out slowly seaward. The cilinder-lens formed by sedimentation is not symmetric, its thickest part being near one side, and that the shore side. This thickest line, as we have seen, becomes the crest, which therefore is asymmetrically placed on the land-side or side from which the sediments were derived. The over-folding on the contrary is to the sea-ward.

SUMMARY STATEMENT OF THE FORMAL THEORY.

We may therefore group all these inferences and sum up our view of the mode of mountain formation thus:

1. Mountain ranges, while in preparation for future birth, were marginal sea-bottoms receiving abundant sediment from an adjacent land-mass and slowly subsiding under the increasing weight. 2. They were at first formed, and continued for a time to grow, by *lateral pressure* crushing and folding the strata together horizontally and swelling them up vertically along a certain line of easiest yielding. 3. That this line of easiest yielding is determined by the hydrothermal softening of the earth's crust along the line of thickest sedimentation. 4. That this line, by softening, becomes also the line of greatest metamorphism; and by yielding, the line of greatest folding and greatest elevation. But (5) when the softening is very great sometimes the harder lateral strata are jammed in under the crest, giving rise to Fan-structure, in which case the most complex foldings may be near but not at the crest. Finally (6) the mountains thus formed will be asymmetric because the sedimentary cilinder-lenses from which they originated were asymmetric.

SOME EXAMPLES ILLUSTRATING.

It is hardly necessary to enforce these views by illustrative examples. They at once arise in the mind of every geologist. But there are those in this audience who are not geologists. I therefore select a few examples among our own mountains.

1. *Appalachian.* It is well known that during the whole Palæozoic, the region now occupied by the Appalachian was the eastern marginal bottom of the great interior Palæozoic Sea, receiving abundant sediments from an eastern land mass of Archæan rocks, which then extended far beyond the present limits of the continent and whose western coast-line was a little to the east

of the present Appalachian crest. The sediments along this marginal sea-bottom increased in thickness during Cambrian, Silurian, Devonian and Carboniferous (with some changes of Physical Geography, but without greatly changing the line of sedimentation) until 40,000 feet thickness was reached. Such thickness, of course, could not be attained without *pari passu* subsidence. We have additional evidence of this in shallow water fossils and even shore marks at many levels in the series. At the end of the coal period, when 40,000 feet had accumulated, the increasing softening along the line caused it finally to yield to horizontal thrust; the whole mass of strata was crumpled together and swelled up along the line of sedimentation and the Appalachian Range was born. The same forces which caused its birth continued to cause its *growth* for a long time. Subsequent erosion has sculptured it into its present form, but *has not exposed its granite core.* The crest is on the east or landward side, as we should expect, and the overfolds are to the west or toward the sea of that time. This is perhaps the most typical example we have.

2. *Sierra.*—If it were not for a subsequent movement so late as the beginning of the Quaternary, which greatly modified its form, the Sierra too would be a typical range. During the whole Palæozoic and the greater part of the Mesozoic the place now occupied by the Sierra was the eastern marginal bottom of the Pacific, receiving sediments from a continental land-mass in the present Basin region. The shore line changed somewhat at the end of the Palæozoic, but the Sierra region maintained a sea bottom position. At the end of the Jura, when an enormous thickness had accumulated, the increasing softening of the crust determined a yielding to lateral thrust and consequent formation of the range. Subsequent erosion has completely removed the strata from the crest and exposed the granitic core as an axis[1]. This axis is here also on the landward side, and the overfolds are

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[1] Sierra granite is not Archæan as has been asserted by some, nor does it all antedate the birth of the range. This is proved (1) by the gradation traceable between slates and granites, and (2) by the fact stated by Whitney, by Fairbanks, and by Diller—that the granite in many places penetrates the slate as veins.

to the seaward as in the Appalachian. The erosion of the Cretaceous and Tertiary times probably cut down the Sierra to very moderate proportions and reduced it to an almost senile condition. At the end of the Tertiary a great fault and bodily uplift of the whole Sierra block on its east side transferred its crest to the extreme eastern margin, greatly increasing its height and rejuvenating its erosive vigor.

3. *Coast Range.*—The formation of the Sierra transferred the coast line westward of that range and the present place of Coast Range became marginal sea-bottom, receiving sediment from a now greatly increased land-mass. This continued until the end of the Miocene when the Coast Range was similarly formed.

We might multiply examples, but these are deemed sufficient to illustrate the principles.

MINOR PHENOMENA.

We have given only the most fundamental phenomena, *i.e.*, those which reveal the mode of origin, and upon which, therefore, a true theory must be founded. But all other minor phenomena associated with mountains are well explained by the view above presented and their explanation confirms the view. For example:

1. *Eruptive Phenomena.*—We have seen that beneath a mountain, before and at the time of its formation, there is a deep-seated core of liquid or semiliquid matter. Also it is evident that the strong foldings of the strata in the act of mountain formation must produce fissures parallel to the folds and to the mountain axis, and that these fissures may reach down to the submountain liquid matter. In the act of mountain formation, therefore, the submountain liquid must be squeezed into the fissures forming dikes, or through the fissures and poured out on the surface as great lava floods, covering sometimes thousands of square miles. In most cases subsequent erosion has swept these overflows clean away leaving only their roots as intersecting dikes. Only the most recent still remain. On these great fissure-eruption lava-fields, ordinary volcanic or crater eruptions continue for ages

after the mountain formation ceases. In these, however, materials are ejected not by mountain-making forces, but by the elastic force of vapor from percolating waters. All these eruptive phenomena are, therefore, associated with mountain ranges.

2. *Faults.*—In folding, and especially overfolding, the strata are, of course, often broken and the upper wall of the fissure is pushed over the lower wall by horizontal thrust often thousands of feet, forming reverse faults and so-called thrust planes. Hence this style of faults are everywhere associated with strongly folded rocks, and, therefore, with mountains, and are indisputable evidence of horizontal crushing. In other places than mountains, and in horizontal or gently folded rocks, the other style of faults, *i. e.*, normal faults, are more common.

3. *Mineral Veins.*—The filling of fissures at the moment of formation with fused matter constitute dikes; but if not so filled, they are afterwards filled by a slow process of deposit from circulating waters and then they form mineral veins. These, therefore, are also common in mountains.

4. *Earthquakes.*—Again, the immense dislocations of strata which we find in faults did not occur all at once, but slowly through great lapse of time; and yet on the other hand not by uniform slipping, but by jerks, a little at a time. Every such readjustment of the walls of a fissure, whether by increasing lateral pressure (reverse faults) or by gravity (normal faults), gives rise to an earthquake. Earthquakes, therefore, although not confined to, are most common in mountain regions, especially if the mountains are still growing.

Thus, leaving out the monoclinal type which seems to belong to different category, all the phenomena, major and minor, of structure and of occurrences connected with mountains, are well explained by the theory of *lateral pressure* acting on lines of thick sediments accumulated on marginal sea-bottoms and softened by invasion of interior heat. This view is therefore satisfactory as far as it goes, and brings order out of the chaos of mountain phenomena. It has successfully directed geological investigation in the past and will continue to do so in the future.

But there still remains the question: "*What is the cause of the lateral pressure?*" The answer to this question constitutes the *physical theory.*

Thus far I suppose there is little difference of opinion. I have only tried to put in clear condensed form what most geologists hold. But henceforward there are the most widely diverse views and even the wildest speculations. But let us not imagine, on that account that we have made no progress in the science of mountain-origin. The *formal theory* already given is really for the geologist by far the most important part of the theory of mountain-origin. For I insist that for the geologist *formal* theories are usually more important than *physical* theories of geological phenomena. That slaty cleavage is the result of a mashing of strata by a force at right angles to the cleavage-planes, is of capital importance to the geologist, for it is a guide to all his investigations. To what property of matter this structure is due is of less importance to him, though of prime importance to the physicist. That the phenomena of the drift is due to the former existence of a moving ice-sheet is the one thing most important to the geologist, guiding all his investigations. Whether this ice-sheet was caused by geographical or astronomical changes is a question of wider but of less direct interest to him. So in the case of mountain ranges, the most important part of the theory is their origin by lateral pressure under the conditions given above. The *cause* of the lateral pressure, though still of extreme interest, is certainly of less immediate importance in guiding investigations.

PHYSICAL THEORIES.

The most obvious view of the cause of lateral pressure refers it to the *interior contraction of the earth.* This may be called the

"CONTRACTIONAL THEORY."

This theory is so well known that I will give it only in very brief outline. It assumes that the earth was once an incandescent liquid and has cooled and solidified to its present condition. At first it cooled most rapidly at the surface and must have fissured by tension. But there would inevitably come a time when the surface being substantially cool and moreover receiving heat also from the sun, its temperature would be fixed or nearly so, while the incandescent interior would be still cooling and contracting. Such has probably been the case ever since the commencement of the *recorded* history of the earth. The hot interior now cooling and contracting more rapidly than the cool crust, the latter following down the ever shrinking nucleus would be thrust upon itself by lateral pressure with a force which is simply irresistible. If the crust were ten times, yea one hundred times more rigid than it is, it must yield. It does yield along the lines of greatest weakness, *i. e.*, along marginal sea-bottoms as already explained. As a first attempt at a physical theory, it seems reasonable, and therefore, until recently, has been generally accepted.

OBJECTIONS TO THE CONTRACTIONAL THEORY.

It is well known that American geologists have taken a very prominent part in the study of mountain structure and mountain origin. So much so indeed that the *lateral pressure theory* in the form given above and interior contraction as its cause, have sometimes been called the "American theory." It is also well known that my name, among others, especially Dana's, has been associated with this view. All I claim is to have put the whole subject, especially the formal theory, in a clearer light and more consistent form.[1] The formal theory I regard as a permanent acquisition. The contractional theory may not be so. It is natural, from my long association with it, that I should be reluctant to give it up. But I am sure that I am willing to do so if a better can be offered. We all dearly love our own intellectual children, especially if born of much labor and thought; but I am sure that I am willing, like Jephtha of old, to sacrifice, if need be, this my fairest daughter on the sacred altar of Truth. Objections have recently come thick and fast from many directions. Some of these

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[1] "Theory of the Formation of the Great Features of the Earth's Surface." Am. Journal, Vol. 4, pp. 345 and 460, 1872, and also "Structure and Origin of Mountains," Vol. 16, p. 95, 1878.

I believe can be removed ; but others perhaps cannot in the present condition of science, and may indeed eventually prove fatal. Time alone can show. I state briefly some of these objections.

1. Mathematical physicists assure us that on any reasonable premises of initial temperature and rate of cooling of the earth, the *amount* of lateral thrust produced by iuterior contraction would be wholly insufficient to account for the enormous foldings.[1] Let us admit—surely a large admission—that this is so. But this conclusion rests on the supposition that the whole cause of interior contraction is *cooling*. There may be other causes of contraction. If cooling be insufficient, our first duty is to look for other causes. Osmund Fisher has thrown out the suggestion (a suggestion by the way highly commended by Herschel) that the enormous quantity of water vapors ejected by volcanoes and the probable cause of eruptions is not meteoric in origin as generally supposed, but is original and constituent water occluded in the interior Magma.[2] Tschermak has connected this escape of constituent water from the earth with the gaseous explosions of the sun.[3] Is it not barely possible that we may have in this an additional cause of contraction, more powerfully operative in early times but still continuing? See the large quantity of water occluded in fused lavas to be "*spit out*" in an act of solidification! But much still remains in volcanic glass which by refusion intumesces into lightest froth. Here then, is a second possible cause of contraction. If these two be still insufficient, we must look for still other causes before rejecting the theory.

2. Again: Dutton[4] has shown that in a *rigid earth* it is impossible that the effects of interior contraction should be concentrated along certain lines so as to form mountain ranges, because this would require a shearing of the crust on the interior. The yield-

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[1] Cam. Phil. Trans. Vol. XII., Part II., Dec. 1873.

[2] Cambridge Phil. Trans. Vol. XII., Part II., Feb. 1875. Physics of the Earth's Crust, p. 87.

[3] Geol. Mag. Vol. IV., p. 569, 1877.

[4] Am. Jour. Vol. VIII., p. 13, 1874. Penn. Monthly, May, 1876.

ing according to him would be evenly distributed everywhere and therefore imperceptible anywhere. This is probably true, and therefore a valid objection in the case of an earth *equally rigid in every part.* But if there be a sub-crust layer of liquid or semi-liquid or viscous, or even more movable or more unstable matter, either universal or over large areas, as there are many reasons to think, then the objection falls to the ground. For in that case there would be no reason why the effects of general contraction should not be concentrated on weakest lines as we have supposed.

3. But again: it has been objected that the lines of yielding to interior contraction ought not to run in *definite* directions for *long distances,* but irregularly in *all* directions. I believe we may find the answer to this objection in the principle of flow of solids under very slow heavy pressure. The flow of the solid earth, under pressure in *many* directions, might well be conceived as being deflected to the direction of least resistance, *i. e.*, of easiest yielding.

4. But again: it will be objected that the amount of circumferential shortening necessary to produce the foldings of some mountains is simply incredible; for it would disarrange the stability of the rotation of the earth itself. According to Claypole, in the formation of the Appalachian range, the circumference of the earth was shortened eighty-eight miles and in the formation of the Alps seventy-two miles. Now this would make a decrease of diameter of the earth of twenty-eight miles in the one case and twenty-three in the other. This would undoubtedly seriously quicken the rotation and shorten the day. This seems indeed startling at first. But when we remember that the tidal drag is all the time retarding the rotation and lengthening the day and much more at one time than now, we should not shrink from acceptance of a counteracting cause hastening the rotation and shortening the day, and thus giving stability instead of destroying it. We must not imagine that there would be anything catastrophic in this readjustment of rotation. Mountains are not formed in a day nor in a thousand years. It requires

hundreds of thousands of years, or even millions of years—if physicists allow us so much.

The objections thus far brought forward, though serious, are by no means unanswerable. But there is one brought forward very recently which we are not yet fully prepared to answer and may possibly prove fatal.

5. *Level of No Strain.*—Until recently the interior contraction of the earth was considered only roughly and without analysis. It was seen that the surface was already cool and its temperature fixed while the interior was still hot and cooling; and therefore that the exterior must be thrust upon itself and be crushed. But the phenomena are really far more complex than at first appears. It is necessary to distinguish between two kinds of contraction to which the interior layers are subjected, viz., radial and circumferential. If there were radial contraction only, then undoubtedly every concentric shell as it descended into smaller space would be crushed together laterally. But there is for all layers, except the surface, also a circumferential contraction, and this would have just the opposite effect, *i.e.*, would tend to stretch instead of crush. Therefore wherever the decrease of space by descent is greater than the circumferential contraction, there will be crush, and where the circumferential contraction is greater than the decrease of space by descent, there will be tension and tendency to crack. There would be no *real* cracking, only because incipient cracks would be mashed out or rather prevented by superincumbent pressure. Where these two are equal to one another, there will be no strain of any kind. There is a certain depth at which this is the case. It is called the "*level of no strain.*" To Mellard Reade is due the credit of first calling attention to this important principle.

Let us analyze the principle more closely. It is admitted that at the surface there is no contraction of any kind. It is also calculated that contraction of all kinds cease at depth of 400 miles. It is believed farthermore that commencing 400 miles below the surface and coming upward the contraction increases very slowly from zero to a maximum at the depth of 70 miles and then decreases again more rapidly to zero at the surface. This is shown in diagram, Fig. 1. In this figure the curve represents the relative rate of contraction whether radial or circumferential of the several layers. We use it, however, only to represent the latter. For in considering the radial contraction, it is not the relative rate of the several layers that immediately concerns us, but their rate of *radial descent*. Now this is a *summation series* and therefore increases to the very surface, but at different rates of increase. The law of increase of radial descent as we come toward the surface is shown in diagram, Fig. 2[1] in which the rate of increase is greatest at seventy miles, just where the curve changes from concavity to convexity. If now we superpose these two diagrams the depth *a* at which the two curves,

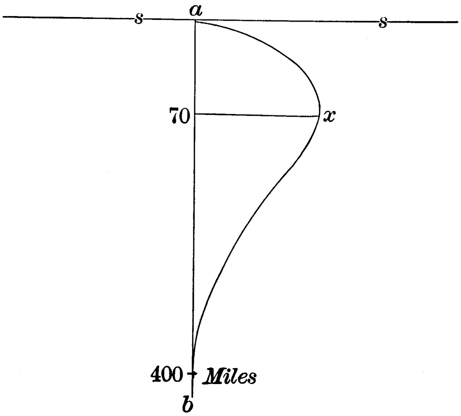

FIG. 1. *s s*=Surface; *a b*=depth along radius; *a x b*=curve of contraction.

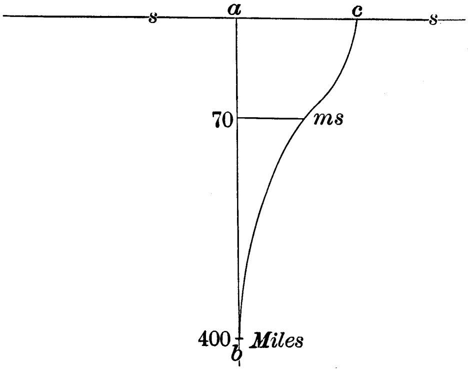

FIG. 2. *c b*=curve of radial descent.

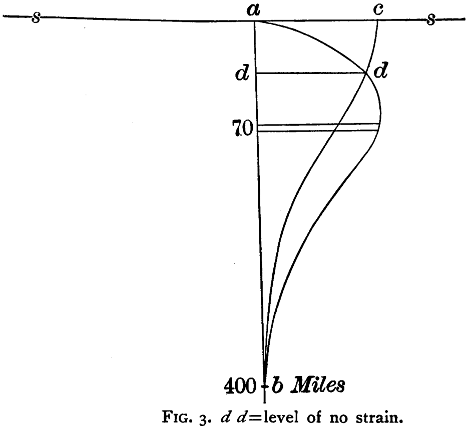

FIG. 3. *d d*=level of no strain.

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[1] I have taken these figures from Claypole, but modified this one so as to make it a truer representation of the law.

viz., that of circumferential contraction and that of radial descent, intersect, is the level of no strain.

Now laborious calculations have been made by Davison, Darwin and Fisher to determine the depth of this level of no strain. All make it very superficial. Davison, taking an initial temperature of 7000° F., makes it five miles below the surface. Fisher, on the same data, only two miles, and with an initial temperature of 4000° only *0.7* of a mile. It is easy to see that if this be true, the amount of lateral thrust must be small indeed.

Now undoubtedly there is a true principle here which must not hereafter be neglected, but it is almost needless to say that these quantitative results are in the last degree uncertain. The calculations are, of course, based on certain premises. These are a uniform initial temperature of say 7000° F., a time of cooling, say 100 or 200 millions of years, and a certain rate of cooling under assumed conditions. The depth of the level of no strain increases with the time and is still going downward. In a word, in a question so complex both mathematically and physically and in which the data are so very uncertain, every cautious geologist, while freely admitting the soundness of the principle, will withhold assent to the conclusions. Huxley has reminded us that the mathematical mill, though a very good mill, cannot make wholesome flour without good wheat. It grinds indifferently whatever is fed to it. It has been known to grind peas cods ere now. It may be doing so again in this case. Let us wait.

But besides withholding assent and waiting for more light, I may add that these calculations, of course, go on the supposition that the whole contraction of the earth is due to loss of heat; but as we have already said, it may be due also to loss of constituent water. This would put an entirely different aspect on the subject.

ALTERNATIVE PHYSICAL THEORIES.

I have given the objections to the contractional theory frankly and I think fairly. They are undoubtedly serious. Let us see what has been offered it its place.

I. READE'S EXPANSION THEORY.

This, the most prominent among alternative theories, was first brought forward in Mr. Reade's book on "Origin of Mountain Ranges." Although I have carefully read all that Mr. Reade has written on the subject, I find it difficult to get a clear idea of his views. But, as I understand it, it is in outline as follows: (1) Accumulation of sediments off shore and isostatic subsidence of the same. (2) Rise of isogeotherms and heating of the whole mass of sediments and of the underlying crust in proportion to the thickness of the sediments. (3) *Expansion* of the whole mass in proportion to the rise of temperature. If there were no resistance, this expansion would be in all directions (cubic expansion). (4) But since the containing earth will not yield to expansion laterally, this lateral expansion is satisfied by *folding*, and this in turn produces *vertical upswelling*. Thus the whole *cubic expansion is converted into vertical expansion*, which is therefore three times as great as the linear expansion in any one direction. (5) Elevation would of course anyhow be greatest along the line of thickest sediment; but this by itself would not be sufficient to produce a mountain. (6) But farther—and here the theory is more obscure—there is a concentration of the effects of expansion, along a comparatively narrow line of thickest sediment, by a *flow* of the hydrothermally plastic or even liquid mass beneath, *toward* this central line and then *upward* through the parted strata, folding these back on either side and appearing at the crest as the granitic or metamorphic axis. (7) In his latest utterances he seems to adopt the view of Reyer, viz., that the uplifted strata slide back down the slope, producing the enormous crumpling so often found, and exposing a wider area of granite axis. (8) From the same liquid mass which lifts the mountain, come also the great fissure eruptions and the volcanoes.

Mr. Reade makes many experiments to determine the linear expansion of rocks, and he thinks that these experiments show that when cubic expansion is converted into vertical expansion and this again concentrated along a line one-fourth to one-fifth the whole breadth of the expanding mass, it would explain the elevation of the highest mountains. But still he seems uncertain if it be enough. In fact, he declares that if it were not for another factor yet unmentioned, he probably would never have brought forward the theory at all.

(9) This factor is *recurrency of the cause and accumulation of the effects.* And here the previous obscurity becomes intensified. I have read and re-read this part without being able wholly to understand him. He seems to think that when expansion had produced elevation, the mountain thus formed would not come down again by cooling and contraction; but on the contrary would *wedge up by normal faulting and set in its elevated position.* Afterward, by new accumulation of heat, another elevation and setting would take place and the mountain grow higher, and so on indefinitely, or until the store of heat is exhausted. Therefore he characterizes his theory as that of "*Alternate expansion and contraction,*" or again as that of "*Cumulative recurrent expansion.*"

Such is a very brief, perhaps imperfect, but I hope fair outline of Reade's theory. It seems to me that there are fatal objections to it. These I now state.

Objections.—1. The first is *inadequacy* to account for the enormous foldings of the mountains especially when there is no granite axis to fold back the strata. It is true that Mr. Reade makes comparison between his own and the contractional theory in this regard, and seems to show the much greater effectiveness of his own. This may be true if we accept his premises and compare *equal areas* in the two cases. But the contractional theory *draws from the whole circumference* of the earth and *accumulates* the effects on one line, while in Reade's theory the expansion is, of course, very *local.*

2. But the fatal objection is that brought forward by Davison. It is this: sedimentation cannot, of course, increase the sum of heat in the earth. Therefore the increased heat of the sediments by rise of isogeotherms, *must be taken from somewhere else.* Is it taken from below? Then the radius below must contract as much as the sediments expand and therefore there will be no elevation. Is it taken from the containing sides? Then

the sides must lose as much as the sediments gain, and therefore must contract and make room for the lateral expansion, and therefore there would be no folding and no elevation. I do not see any escape from this objection.

Thus it seems that Reade's theory cannot be accepted as a substitute. Is there any other?

II. DUTTON'S ISOSTATIC THEORY.[1]

Dutton's discussion of isostasy is admirable, but his application of it to the origin of mountains is weak. The outline is as follows:

Suppose a bold coast line, powerful erosion and abundant sedimentation. The coast rises by unloading and the marginal sea-bottom sinks by loading. Now if isostasy is perfect, there will be no tendency to mountain formation. But suppose a piling up of sediments, but—on account of earth rigidity—without immediate compensatory sinking, and a cutting down of coast land without compensatory rising. Then *there would be an isostatic slope toward the land.* And the accumulated and softened sediments would *slide landward, crumpling the strata and swelling them up into a mountain range.*

The fatal objection to this view is that complete isostasy is necessary to renew the conditions of continued sedimentation and therefore to make thick sediments, otherwise the sediments quickly rise to sea-level and stop the process of sedimentation at that place. But it is precisely a *want* of complete isostasy which is necessary to make an isostatic slope landward. Dutton refers to Herschel as having suggested a similar cause of strata crumpling and slaty cleavage[2]; but the principles involved in the two cases are almost exactly opposite. Herschel supposes sediments to slide down steep *natural* slopes of sea-bottoms and therefore *seaward.* Dutton supposed sediments to slide *up* natural, though *down* isostatic slopes, *landward.* Herschel's is a theory of strata-crumpling and slaty cleavage; Dutton's a theory of mountain formation.

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[1] Phil. Soc. of Washington, Bull. Vol. XI, pp. 51–64, 1889.

[2] Phil. Mag., Vol. 12, 197, 1856.

There has been no attempt to carry this idea of Dutton's to quantitative detail. It was probably thrown out as a suggestion in mere despair of any other explanation, for he had already repudiated the contractional theory. But the least reflection is sufficient to convince that such slight want of complete isostatic equilibrium as may sometimes occur would be utterly inadequate to produce such effects.

III. REYER'S GLIDING THEORY.[1]

Prof. Reyer has recently put forward certain views fortified by abundant experiments on plastic materials. His idea in brief seems to be this: Strata are lifted and finally broken through by up-rising fused or semi-fused matters and these appear above as the granitic axis. As the axis rises, the strata are carried upward on its shoulders, until *when the slope is sufficiently steep the strata slide downward crumpling themselves into complex folds* and exposing the granitic axis in width proportioned to the amount of sliding.

No doubt there is much value in these experiments of Reyer, and possibly such gliding does indeed sometimes take place in mountain strata and some foldings may be thus accounted for. But the great objections to this view are (1) that there is no adequate *cause* given for the *granitic uplift*, and (2) that it utterly fails to account for the complex foldings of such mountains as the Appalachian and Coast Range *where there is no granite axis at all*. Reade, indeed, holds that the Piedmont region is the granite axis of the Appalachian, and that the original strata of the eastern slope are now buried beneath the sea. But American geologists are unanimous in the belief that the shore line of the great interior Palæozoic sea was but a little east of the Appalachian crest and the sea washed against land of Archæan rocks extending eastward from that line.

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[1] Nature, Vol. 46, p. 224, 1892, and Vol. 47, p. 81, 1892.

CONCLUSION.

After this rapid discussion of alternative theories in which we have found them all untenable, we return again to the contractional theory, not indeed with our old confidence, but with the conviction that it is even yet the best working hypothesis we have.

JOSEPH LE CONTE.